Cluster and Representative Models for Generation Units of Flexible Grids with Small Modular Reactors

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The analysis of existing mathematical models for power systems with large shares of electricity production by NPP and renewable energy sources generation was carried out. The low level of adequacy is shown for power system models used in the problems of long-term development planning for generating plants with nuclear fuel and renewable energy sources. In order to plan the development of power systems at the current stage of technological changes in the electric power industry, new models of load modes for NPP units and generating equipment with renewable energy sources are proposed.

Dispatching models with a cyclic forecast period were used to ensure the adequacy unit commitment models for NPP units and energy storage systems. Representative models of solar and wind power plants are presented, which, together with cluster models of NPP units and energy storage systems, solve the issue on the adequacy of power system modeling in current conditions of their development. The results of computational experiments with the proposed models for generating equipment of the flexible grid are presented. The adequacy of cluster mathematical models of NPP units and energy storage systems, as well as representative models of solar and wind power plants generating equipment is experimentally confirmed.

Keywords: cluster model, flexible grid, generation unit, local grid, representative model.

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Introduction

The conditions for electric power industry development are in the state of drastic changes.

Climate change has become one of the main challenges of human development. The production of electricity and heat is accompanied by the release of up to 40% of total CO₂ emissions. Therefore, the main trend in the development of generation is the abandonment of organic fuel, the development of renewable energy sources (RES), and the revival of interest in nuclear energy.

The volume of electricity production by solar and wind power plants (SPPs and WPPs) is completely dependent on weather conditions characterized by variability and poor predictability. This causes problems in ensuring the reliability of power supply. As a result, traditional power generation technologies bear a significant burden of power regulation.

The development of nuclear power plants (NPPs) equipped with small modular reactors (SMRs) opens up new perspectives [1]. They have high maneuverability characteristics, so their construction increases the flexibility of the power system. The deployment of SMRs could help to decentralize the power system and to reduce its vulnerability to military or terrorist attacks. Finally, the use of SMRs reduces polluting emissions and the consumption of imported fossil fuels, thus reducing the environmental impact of the power industry and increasing the energy security of the country and the region.

Modeling generation capacity (CP) evolution is one of the most important and complex tasks in the power sector.

In the conditions of intensive development of RES and energy storage systems (ESS), long-term planning of power system development requires a well-founded determination of the equipment
operating modes during the entire forecast period. At the same time, world-wide platforms for long-term modeling of power systems such as MARKAL, TIMES, LEAP have limited opportunities to adequately reproduce the variable modes of loading generating units [2].

To determine the modes of generating equipment operation the unit commitment (UC-) models are used [3, 4, 5], which take into account their maneuverable characteristics.

To plan the development of power systems with a high share of RES, it is necessary to apply a new architecture of models. It requires solving an optimization problem (CP-problem) formulated based on the set of dispatching problem solutions (UC-problems) for all time periods of the planning horizon.

One of the methods of solving these complex problems is the soft-linking method [4, 6, 7], which consists in sequentially solving the CP-problem with specifying the forecast of generating equipment operation modes by solving UC-problems. That is, the search for a solution to the CP-problem is carried out by an iterative procedure.

Another approach is to use strong links between CP and UC tasks. The integral CP&UCs problem of the operation and development of generating capacity [8, 9] includes both capital costs and start-up and operation costs of power units as part of the functionality. The CP&UCs problem is a mixed integer linear programming problem of high dimensionality, so it is important to choose the optimal ratio of system description detail and computational complexity.

Detailed time reproduction of RES load modes over long-term forecast periods requires the aggregation of historical data. Representation of RES electricity production volumes in the form of averaged daily and weekly graphs, by analogy with electricity demand graphs, leads to a distorted display of RES operating modes in the most critical operating modes for the power system. The papers [10, 11] propose data clustering methods for the model representation of RES production schedules. The most attractive are hierarchical methods, in particular the method of agglomerative clustering, whose results do not depend on the initial division of the original data into clusters [12].

In traditional CP models, equipment state is not specified at the beginning of the forecasting stage. In the CP&UCs task, in order to correctly determine the operating modes of the equipment, it is necessary to reasonably establish initial equipment state for each forecast period. To overcome this limitation UCC-model is proposed, it reproduces units loading modes on a cyclical weekly forecast horizon and does not require initial unit states, as it establishes a relationship between units' states at the end and beginning of the forecast horizon [13].

The aim of this paper is to develop a model for the development of a flexible grid that should be formulated in the form of CP&UCs problem, provide modeling on a cyclic forecasting horizon and use representative RES models.

1. Representative models of WPPs and SPPs

The efficiency of WPP and SPP operation is determined by the ratio of the electricity production amount to its installed capacity and is represented by a weekly graph of the capacity factor. Such graphs obtained for the Ukrainian WPPs and SPPs, which were involved in the production of electricity in the winter periods of 2019-2021, are presented in Figure 1.

In order to provide an adequate model representation of the weekly variability for WPP and SPP capacity factors, it is necessary to analyze their sample means and sample variances and to determine representative graphs based on these indicators.

Figure 1 – Weekly graphs of the capacity factors of Ukrainian WPPs and SPPs. Actual graphs are shown as thin gray lines, and their averaged graphs are shown as bold black lines.
Below, there is a method of determining a representative graph, the sample mean and sample variance of whose values are at the minimum departure from the average values of these indicators, calculated for the entire set of graphs of WPP and SPP capacity factors.

Let’s consider a set of weekly graphs of electricity production volumes of an individual power plant (WPP or SPP) for several previous years and evaluate the value of the capacity factor

$$E_{y,m,w,t} = \frac{V_{y,m,w,t}}{N_{y,m}},$$

(1)

where $N_{y,m}$ is the installed capacity of the power plant as of the month $m \in \{1,2,\ldots,12\}$ of the year $y \in \{Y\}$, and the electricity production $V_{y,m,w,t}$ per hour $t \in \{T\}$ of the week $w \in \{1,2,3,4\}$ of that month $m$ of the year $y$.

For each week $w$ of the month $m$ of the year $y$, we determine the sample mean of the set of values of the capacity factor

$$Avg_{y,m,w} = \frac{1}{|\{1,2,\ldots,T\}|} \sum_{t \in \{T\}} E_{y,m,w,t},$$

and its sample variance (unbiased estimate)

$$Var_{y,m,w} = \frac{1}{|\{1,2,\ldots,T\}| - 1} \sum_{t \in \{T\}} (E_{y,m,w,t} - Avg_{y,m,w})^2.$$

For $\forall m \in \{1,2,\ldots,12\}$ calculate the mean values of values $Avg_{y,m,w}$ and $Var_{y,m,w}$ for the multi-year observation period, respectively

$$\overline{Avg}_y = \frac{1}{4|\{1,2,3,4\}|} \sum_{y \in \{Y\}} \sum_{w \in \{1,2,3,4\}} Avg_{y,m,w},$$

$$\overline{Var}_y = \frac{1}{4|\{1,2,3,4\}|} \sum_{y \in \{Y\}} \sum_{w \in \{1,2,3,4\}} Var_{y,m,w},$$

Then, among the available set of points $(Avg_{y,m,w}, Var_{y,m,w})$, we will find one that is minimally distant from the point $(\overline{Avg}_y, \overline{Var}_y)$, that is, we will solve the problem

$$\Phi_y(y,w) = \sqrt{(\overline{Avg}_y - A_{y,m,w})^2 + (\overline{Var}_y - V_{y,m,w})^2}$$

(2)

For a month $m$, the solution $(y_{opt}, w_{opt})$ is a weekly graph of the variability of the capacity factor $E_{y_{opt},m,w_{opt},t}$, which is a representative graph for a set of graphs $E_{y,m,w,t}$ based on the sample mean and sample variance. The graph $E_{y_{opt},m,w_{opt},t}$ represents the entire set of available graphs $E_{y,m,w,t}$ of the month $m$, therefore it is called representative.

Using a representative graph $E_{y_{opt},m,w_{opt},t}$ and relation (1), it is possible to determine the hourly amounts of electricity production using the expression

$$V_{y,m,w,t} = E_{y_{opt},m,w_{opt},t}N_{y,m}.$$  

(3)

The resulting relationship (3) is called a representative model of WPPs or SPPs.

2. Representative models of WPPs and SPPs on clusters

We will use Ward’s method of agglomerative data clustering, which, when combining a pair of clusters, ensures a minimal increase in the intra-cluster dispersion of data. As a result of applying the method of agglomerative clustering of data, presented in the form of graphs of capacity factors of WPPs or SPPs, for $\forall m \in \{1,2,\ldots,12\}$ and predetermined set of clusters $K$, we will obtain a division of the existing set $\Lambda$ of graphs $\{E_{y,m,w,t}: t \in \{T\}\}$ into clusters $\{E_{y,m,w,t}(k), t \in \{T\}\}$ with $\Lambda$ graphs in each cluster $k \in K$. Note that

$$\sum_{k \in K} \Lambda_k = \Lambda.$$

Let’s apply criterion (2) to the set of graphs $\{E_{y,m,w,t}(k), t \in \{T\}\}$ of each cluster $k \in K$. As a result, we will find representative graphs $E_{y_{opt},m,w_{opt},t}(k)$, $\forall k \in K$. For example, for the graphs presented in Figure 1 we have representative graphs presented in Figure 2.

In order to increase the adequacy of the modeling of electric power systems with a large share of WPPs and SPPs, it is necessary to abandon using averaged graphs of WPP and SPP capacity factors and use their representative cluster models in the form of ratios

$$V_{y,m,w,t} = E_{y_{opt},m,w_{opt},t}(k)N_{y,m},$$  

(4)

which have a weighted impact factor $\Lambda_{y,m}/\Lambda$ on the corresponding forecast period, where $k \in K$.

The use of representative cluster models of WPPs and SPPs in power system modeling problems leads to a rise in the dimensionality of such tasks. Instead of daily or weekly averaged graphs, which usually refer to each month of the forecast year, it is necessary to use representative sets of weekly graphs, which increases the dimensionality of the tasks by one time. Therefore, using representative models of WPPs and SPPs in power system modeling problems requires a reduction in the dimensionality of such problems, which can be achieved in particular by clustering the same type of generating equipment [8].
3. Cluster models of cyclic load for NPP units and representative models of RES in CP&UCs optimization problem

A. Model parameters:
- $t$ – the number of the time interval of the weekly forecast period $t \in T$
- $z$ – the number of the weekly forecast period $z \in Z$
- $j$ – the number of the annual interval of the forecast period $j \in J$
- $k$ – the number of cluster $k \in K$
- $\tau_z$ – the duration of the forecast period $z$ in weeks
- $Z_z$ – a set of numbers $z$ in the year $j$
- $\Lambda_k, \Lambda_z$ – the number of weekly functions of the $k$ cluster for the period $z$
- $\Lambda_y$ – the total number of weekly functions clustered for the period $z$
- $E_i, t$ – the value of the representative weekly graph for the capacity factor of the RES generating plant of $i$ type in time $t \in W_{t,j}$
- $W_{t,j}$ – a set of numbers of time intervals of the weekly cluster $k$ for the forecast period $j$
- $y$ – discount rate
- $F, S, R$ – a set of available types of NPP units, ESS and RES
- $i$ – the number of the power plant type
- $P^\text{tech}_i$ – the installed capacity of the $i$ type power plant
- $N_{ij}$ – the number of the $i$ type new equipment considered to be put into operation at the beginning of the forecast year $j$
- $N_i$ – the number of $i$ type units available at the beginning of the period
- $T_j$ – the number of the extreme right time interval of the weekly period
- $\tilde{c}_i, c_i$ – the cost of NPP unit startup and shutting down
- $\tilde{C}$ – operating costs at minimum load NPP unit
- $\tilde{c}$ – the coefficient of elasticity of operating costs to the load of NPP units
- $C^\text{con}_i$ – capital costs for the $i$ type unit construction
- $P^\bar{F}_i, P^\tilde{F}_i$ – the minimum and maximum loads of NPP unit
- $P^\text{su}_i$ – the lower permissible load limit of NPP unit during its startup
- $P^\text{sd}_i$ – the upper permissible load limit of NPP unit before its shutdown
- $\Delta P^\text{su}, \Delta P^\text{sd}$ – the maximum increase and reduction of NPP unit load
- $\eta^\text{sp}, \eta^\text{sg}$ – efficiency of ESS in pump and generator mode
- $c^\text{sp}, c^\text{sg}$ – specific operating costs for ESS in pump and generator mode
- $q^\text{pp}, q^\text{PG}$ – the maximum ESS load in pump and generator mode
- $c^\text{pp}$ – specific operating costs for the production by generation unit
- $\gamma$ – discount rate
- $F, S, R$ – a set of available types of NPP units, ESS and RES
- $i$ – the number of the power plant type
- $N_i$ – the number of $i$ type units available at the beginning of the period
- $T_0$ – the number of the extreme right time interval of the weekly period
- $c^\text{su}, c^\text{sd}$ – the cost of NPP unit startup and shutting down
- $\eta^\text{su}, \eta^\text{sd}$ – efficiency of ESS in pump and generator mode
- $q$ – the amount of energy stored in ESS
- $\eta^\text{sp}, \eta^\text{sg}$ – efficiency of ESS in pump and generator mode
- $\mu^0$ – binary function, which takes a value of 0 when ESSs are operated in pump mode and a value of 1 - in generator mode.

B. Model variables:
- $\text{Cost}$ – operating costs for electricity production by the generation unit
- $\text{Cost}^\text{su}, \text{Cost}^\text{sd}$ – costs for starting up and shutting down NPP unit
- $p, l$ – the load of the unit
- $c^\text{pp}$ – specific operating costs for the production by generation unit
- $\mu^0, \mu^1$ – binary function, which takes a value of 0 when ESSs are operated in pump mode and a value of 1 - in generator mode.
C. The objective function of the CP&UCs optimization problem

Operating costs of electricity production in the power system are minimized:

\[
\sum_{j \in J} \left( 1 + \gamma_j \right) \left( \sum_{i \in FSR} \beta_i \right) C_{ij}^{\text{con}} \left( \tilde{N}_{ij} - \tilde{N}_{i,j-1} \right) + \left( \sum_{i \in FSR} \beta_i \right) C_{ij}^{\text{con}} \left( \tilde{N}_{ij} - \tilde{N}_{i,j-1} \right)
\]

\[
\times \left( \sum_{k \in F} \sum_{j \in J} \lambda_{k,j} \sum_{l \in W_{k,j}} \left( \sum_{i \in FSR} \left( \cos(t_{ij}) + \cos(t_{ij}^{\text{dp}}) \right) \right) \right)
\]

\[
\to \min.
\]

Resource limitation of the amount of capital investment:

\[
\sum_{j \in J} \left( 1 + \gamma_j \right) \left( \sum_{i \in FSR} \beta_i \right) C_{ij}^{\text{con}} \left( \tilde{N}_{ij} - \tilde{N}_{i,j-1} \right) \leq \text{Invest}. \quad (6)
\]

Conditions for positive development of the power system through construction and commissioning of new equipment:

\[
\tilde{N}_{ij} \geq \tilde{N}_{i,j-1}, \forall j \in J, \forall i \in F \cup S \cup R.
\]

Conditions of construction completion at the beginning of the forecast period:

\[
\tilde{N}_{i,0} = 0, \forall i \in F \cup S \cup R.
\]

The following constraints apply to each time slice of the forecast period.

D. Balance of electricity production and consumption

It is represented by equations:

\[
\sum_{j \in J} \sum_{i \in FSR} \left( \tilde{p}_{ij}^s \right) = l_i + \sum_{j \in J} \sum_{i \in FSR} \left( \tilde{p}_{ij}^p \right), \quad (9)
\]

where \( \forall t \in T = W_{k,j}, \forall z \in Z_j, \forall k \in K, \forall j \in J. \)

E. Operating costs for NPP unit

\[
\text{Cost}_{ij} = C_{ij}^{\text{con}} \left( \tilde{p}_{ij} + \tilde{p}_{ij}^p \right), \quad (10)
\]

\[
\tilde{p}_{ij} \leq \left( \tilde{p}_{ij} - \tilde{p}_{ij}^p \right) \tilde{u}_{ij}, \quad (11)
\]

\[
\tilde{p}_{ij} = \tilde{u}_{ij} \tilde{p}_{ij} + \tilde{p}_{ij}^p, \quad (12)
\]

where \( \forall t \in T = W_{k,j}, \forall z \in Z_j, \forall k \in K, \forall j \in J, \forall i \in F. \)

F. The operation mode of NPP unit

It is described by the system of relationship between the binary functions of its state, which has the form:

\[
y_{ij} = x_{ij} = u_{ij} - u_{ij-1}, \quad t = 1, \quad (13)
\]

\[
y_{ij} + x_{ij} \leq N_i + \tilde{N}_{ij}, \quad (15)
\]

\[
u_{ij} \leq N_i + \tilde{N}_{ij}, \quad (16)
\]

where \( \forall t \in T = W_{k,j}, \forall z \in Z_j, \forall k \in K, \forall j \in J, \forall i \in F. \)

G. The cost for starting up NPP unit

\[
\text{Cost}_{ij}^{\text{su}} = C_{ij}^{\text{su}} \tilde{y}_{ij}, \forall t \in T = W_{k,j}, \forall z \in Z_j, \forall k \in K, \forall j \in J, \forall i \in F. \quad (17)
\]

H. The cost for shutting down NPP unit

\[
\text{Cost}_{ij}^{\text{sd}} = C_{ij}^{\text{sd}} \tilde{y}_{ij}, \forall t \in T = W_{k,j}, \forall z \in Z_j, \forall k \in K, \forall j \in J, \forall i \in F. \quad (18)
\]

I. The current maximum attainable load of NPP unit

It is limited by the maximum capacity or its allowable load before shutdown:

\[
p_{ij} \leq p_{ij-1} + \Delta p_{ij}^{\text{up}} u_{ij-1} + \tilde{p}_{ij}^{\text{su}} y_{ij}, t = 1, \quad (19)
\]

\[
p_{ij} \leq p_{ij-1} + \Delta p_{ij}^{\text{up}} u_{ij-1} + \tilde{p}_{ij}^{\text{su}} y_{ij}, \quad (20)
\]

where \( \forall t \in T = W_{k,j}, \forall z \in Z_j, \forall k \in K, \forall j \in J, \forall i \in F. \)

The unit load is limited from the top by its current maximum achievable load:

\[
p_{ij} \leq \tilde{p}_{ij}, \forall t \in T = W_{k,j}, \forall z \in Z_j, \forall k \in K, \forall j \in J, \forall i \in F. \quad (21)
\]

J. The current minimum achievable load of NPP unit

It is limited from the bottom by its current minimum achievable load:

\[
p_{ij} \geq p_{ij-1}, \forall t \in T = W_{k,j}, \forall z \in Z_j, \forall k \in K, \forall j \in J, \forall i \in F. \quad (22)
\]

The current minimum achievable load of NPP unit is limited by the technical capabilities to reduce its load during shutdown:

\[
p_{ij} \geq p_{ij-1} - \Delta p_{ij}^{\text{down}} u_{ij-1} - p_{ij}^{\text{sd}} x_{ij}, t = 1, \quad (23)
\]

\[
p_{ij} \geq p_{ij-1} - \Delta p_{ij}^{\text{down}} u_{ij-1} - p_{ij}^{\text{sd}} x_{ij}, t = 1, \quad (24)
\]

where \( \forall t \in T = W_{k,j}, \forall z \in Z_j, \forall k \in K, \forall j \in J, \forall i \in F. \)

K. Description of ESS

Operating costs of ESS are determined by the formula:

\[
\text{Cost}_{ij} = C_{ij}^{\text{su}} \left( 1 - y_{ij} \right) p_{ij}^s - C_{ij}^{\text{sd}} \left( 1 - y_{ij} \right) p_{ij}^s, \quad \forall t \in T = W_{k,j}, \forall z \in Z_j, \forall k \in K, \forall j \in J, \forall i \in S. \quad (25)
\]
Energy balances of ESS are represented by the equations:

\[ q_{i,t} - q_{i,t-1} = \eta_i^p p_{i,t}^p - \eta_i^p p_{i,t}^G, \forall t \in T = W_{k,z}, t = 1, \forall z \in Z, \forall k \in K, \forall j \in J, \forall i \in S. \] 

(26)

Complemented by the conditions of weekly cyclicity of accumulated energy:

\[ q_{i,z,i} = q_{i,z,i-1}, \forall t \in T = W_{k,z}, \forall z \in Z, \forall k \in K, \forall j \in J, \forall i \in S. \] 

(27)

The amount of stored energy is limited by the ESS energy consumption:

\[ (N_i + \bar{N}_i) q_i \leq q_i \leq (N_i + \bar{N}_i) q_i^m, \forall t \in T = W_{k,z}, \forall z \in Z, \forall k \in K, \forall j \in J, \forall i \in S. \] 

(28)

Limiting the total number of ESSs in the power system:

\[ N_i + \bar{N}_i \leq N_i^m, \forall t \in T = W_{k,z}, \forall z \in Z, \forall k \in K, \forall j \in J, \forall i \in S. \] 

(29)

Generating equipment of ESS working in generator mode is limited:

\[ p_{i,t}^G \leq \eta_i^G N_i^G p_{i,t}^m, p_{i,t}^G \leq (N_i + \bar{N}_i) \bar{p}_i^G, p_{i,t}^G \geq 0, \forall t \in T = W_{k,z}, \forall z \in Z, \forall k \in K, \forall j \in J, \forall i \in S. \] 

(30)

Load limitations of ESSs during their operation in pump mode:

\[ p_{i,t}^p \leq (1 - \eta_i^p) N_i^G p_{i,t}^m, p_{i,t}^p \leq (N_i + \bar{N}_i) \bar{p}_i^G, p_{i,t}^p \geq 0, \forall t \in T = W_{k,z}, \forall z \in Z, \forall k \in K, \forall j \in J, \forall i \in S. \] 

(31)

L. Description of RES power generation systems

Operating costs for the RES production are calculated by the formula:

\[ \text{Cost}_{t,i} = c_{t,i} \left( N_i + \bar{N}_i \right), \forall t \in T = W_{k,z}, \forall z \in Z, \forall k \in K, \forall j \in J, \forall i \in S. \] 

(32)

4. Computer simulation of flexible grid capacity expansion planning

The computer simulation was conducted for the Local Grid (LG), which includes consumers, RES, NPPs on SMRs and ESS.

Starting with the base year of 2020, the following growth rates of electricity consumption have been adopted for each five-year period: 16.7 % – 2025, 11.4 % – 2030, 10.3 % – 2035, 9.3 % – 2040, 8.5 % – 2045, 7.8 % – 2050 (Figure 3).

Representative weekly graphs for the capacity factors of Ukrainian WPPs and SPPs presented in Figure 4 were applied to the autumn-winter and spring-summer seasons of each of the five years of the forecasting horizon.

Figure 3 – Weekly graphs of electricity consumption in summer (left) and winter (right) for the forecast period of 2025-2050

Figure 4 – Sets of representative weekly graphs for the capacity factors of Ukrainian WPPs and SPPs for the summer season
The SPP and WPP cost of electricity generation is 5 $/MWh.

We accept the discount rate per year at the level of 8%.

Specific capital costs for power units are presented in Table 1.

Total capital costs for the development of LG generating capacities during 2020-2050 are limited to M$1,500.0. SMR (NuScale) and ESS characteristics are reflected in Tables 2 and 3 respectively [14].

To perform computational experiments, the proposed mathematical model of the LG system as a mixed-integer programming problem (5) - (32) was implemented in IBM ILOG CPLEX Optimization Studio Version 20.1.

To assess the impact of taking into account clustering and cyclicity, calculations of system development were made for the following options:

A. Without taking into account clustering and cyclicity.
B. Taking into account clustering and without taking into account cyclicity.
C. Taking into account clustering and cyclicity.

The transition from the traditional averaged presentation (Opt. A) to the clustered one (Opt. B) leads to a significant change in the forecast production volumes of SPPs and WPPs (Figures 5, 6). At the same time, there is a significant increase in the unevenness of SPP and WPP production volumes.

Compensation of growing fluctuations in RES production leads to the need to increase the flexibility of the power system and correspondingly change the optimal structure of generating capacities (Figures 7, 8). In particular, the volume of WPP introduction will be significantly reduced. At the same time, the installed capacity of maneuverable NPPs is increasing threefold and the dates for the introduction of ESSs are approaching.

A more significant reduction in the introduction of RES compared to the introduction of NPPs is explained by the low-capacity factors of RES. The volume of energy storage in ESS changes significantly (Figures 9, 10), and the uneven loading of NPP units also increases (Figures 11 and 12).

Table 1 – Specific capital costs for generating equipment

<table>
<thead>
<tr>
<th>Type of equipment</th>
<th>Capacity, MW</th>
<th>Specific capital costs, $/kW</th>
</tr>
</thead>
<tbody>
<tr>
<td>SMR (NuScale)</td>
<td>77.0</td>
<td>5078.0</td>
</tr>
<tr>
<td>ESS</td>
<td>25.0</td>
<td>845.0</td>
</tr>
<tr>
<td>SPP</td>
<td>20.0</td>
<td>569.62</td>
</tr>
<tr>
<td>WPP</td>
<td>20.0</td>
<td>1265.0</td>
</tr>
</tbody>
</table>

Table 2 – SMR characteristics

<table>
<thead>
<tr>
<th>$c^{SU}$</th>
<th>1093.1 $/Start-Up</th>
</tr>
</thead>
<tbody>
<tr>
<td>$c^{SD}$</td>
<td>1337.5 $/Shut-Down</td>
</tr>
<tr>
<td>$P^{SU}$</td>
<td>19.25 MW</td>
</tr>
<tr>
<td>$P^{SD}$</td>
<td>77 MW</td>
</tr>
<tr>
<td>$P_{up}$</td>
<td>30.8 MW/h</td>
</tr>
<tr>
<td>$P_{down}$</td>
<td>30.8 MW/h</td>
</tr>
</tbody>
</table>

Table 3 – ESS characteristics

| $\eta^{c}$ | 0.82 |
| $\eta^{G}$ | 0.85 |
| $c^{c}$    | 30 $/MWh |
| $c^{G}$    | 30 $/MWh |
| $q$        | 100 MWh |
| $q'$       | 0 MWh  |
| $p'$       | 25 MW  |
| $p^{G}$    | 25 MW  |
Figure 7 – Change of generating capacities, Opt. A

Figure 8 – Change of generating capacities, Opt. B

Figure 9 – Volumes of energy storage in ESSs, Opt. A

Figure 10 – Volumes of energy storage in ESSs, Opt. B

Figure 11 – Loading of NPP units, Opt. A

Figure 12 – Loading of NPP units, Opt. B

Figure 13 – Volumes of energy storage in ESS, Opt. C

Figure 14 – Loading of NPP units, Opt. C
When cyclicity is taken into account (Variant C), the need for equal ESS charging at the beginning and end of the forecast period phases leads to a significant change in the energy accumulation in storage systems (Figures 10, 13). In addition, as a result of taking cyclicity into account, a certain change in generating equipment modes is observed (Figures 12, 14).

The cumulative effect of the specified factors caused by taking into account the cyclicity leads to a change in the optimal composition of the generating equipment (Figures 8, 15).

**Conclusions**

Representative models of WPPs and SESs are cluster models that ensure the reflection of the unpredictability and variability for production volumes of the corresponding generating equipment in power system models and significantly increase the adequacy of forecasting the development of generating capacities of power systems with large shares of nuclear and renewable energy. Representative models are an alternative to traditional models of WPPs and SPPs based on averaged graphs of their capacity factors.

UC-models of the cyclic load for NPP units and ESSs ensure the autonomy of model calculations, namely, the costs of electricity production in such models are determined only within the limits of the selected simulation intervals (for example, a week) and are independent of the load modes of the power equipment in the adjacent intervals.

In the proposed representative models of WPPs and SPPs and cluster UC models of the cyclic load for NPP units and ESSs, not binary, but integer variables of their number of start-ups/shut-downs and load are used, which reduces the amount of calculation performed to find solutions to development problems for generating capacities of electric power systems.

The proposed representative models of WPPs and SPPs and cluster UC models of the cyclic load for NPP units and ESSs solve the problem of adequacy of electric power system modeling in current conditions of intensive green energy development.

**References**

Проаналізовано існуючі математичні моделі енергосистем з великими частками обсягів виробництва електроенергії АЕС та виробниками електроенергії з відновлювальних джерел енергії. Показано недостатній рівень адекватності моделей енергосистем, що застосовуються в задачах довгострокового планування розвитку генеруючих установок з ядерним паливом та з відновлювальними джерелами енергії. Для планування розвитку енергосистем на сучасному етапі технологічних змін в електроенергетиці запропоновано нові моделі навантаження енергоблоків АЕС та генеруючого устаткування з відновлювальними джерелами енергії.

Для забезпечення адекватності моделей навантаження енергоблоків АЕС та систем накопичення енергії використано моделі їх диспетчеризації з циклічним прогнозним періодом. Наведено репрезентативні моделі енергетичних установок вітрових та сонячних електростанцій, які супутно з кластерними моделями енергоблоків АЕС та систем накопичення енергії вирішують проблему адекватності моделювання енергосистем в сучасних умовах їх розвитку. Наведено результати обчислювальних експериментів із запропонованими моделями для генеруючого устаткування гнучкої енергосистеми. Експериментально підтверджена адекватність кластерних математичних моделей енергоблоків АЕС та систем накопичення енергії, а також репрезентативних моделей генеруючих установок вітрових та сонячних електростанцій.

Ключові слова: гнучка енергосистема, генеруюча потужність, кластерна модель, локальна мера, репрезентативна модель.

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